Description of the SSFATE Numerical Modeling System

PURPOSE: This technical note describes the numerical modeling system SSFATE (Suspended Sediment FATE), which is being developed to compute suspended sediment fields resulting from dredging operations. Both theoretical aspects of the computations made within SSFATE and application aspects of the shell-based personal computer program are discussed.

BACKGROUND: SSFATE was developed in response to a need for tools to assist dredging project managers confronted by requests for environmental windows. Environmental windows, intended to protect biological resources or their habitats, are requested during the interagency coordination process for dredging projects (Reine, Dickerson, and Clarke 1998). In many cases, decisions regarding environmental windows must be based on limited technical information because potential impacts are linked to a host of site- and project-specific factors. For example, navigation dredging operations in different reaches of the same waterway may pose risks to different resources, or potential impacts may vary dependent on the type of dredge plant involved. Few tools exist to evaluate such concerns early in the environmental window negotiation process. Consequently, a general inability to address "What if" questions associated with given dredging project scenarios tends to ensure that recommended environmental windows are conservative, and perhaps over-restrictive (Reine, Dickerson, and Clarke 1998).

Some of the most frequently asked "What if" questions during dredging project coordination are related to resuspension and dispersion of sediments at the dredging site. Suspended sediments are a primary concern of resource agencies, as exposure of aquatic organisms to elevated suspended sediment concentrations is perceived to be a major source of detrimental impact. Likewise, redeposition of suspended sediments can be a significant concern if sensitive bottom-dwelling organisms (e.g., oysters or sea grasses) are present in the vicinity of a dredging project. Accurate information on the spatial dynamics of dredge-induced suspended sediments is therefore a critical necessity in establishing the overall need for protective windows.

Environmental windows are associated with a majority of dredging projects in many U.S. Army Corps of Engineers Districts (Reine, Dickerson, and Clarke 1998). However, presently available modeling tools for predicting suspended sediment behavior were not designed with environmental windows negotiation in mind. For logistical reasons, models that require complicated, extensive hydrodynamic databases, grid building, or high-end computer support are not suitable. These models are more appropriate for large, controversial projects. Clearly, funding constraints alone would hinder application of expensive numerical models to the evaluation of numerous environmental windows.

To be truly effective as a dredging project management tool with respect to windows, models should be capable of running multiple simulations in a relatively short span of time so that a number of alternative dredging scenarios can be evaluated to determine those with the least probabilities of

detrimental impacts. An ability to display the dispersion of suspended sediments from a dredging site in a format that can be merged with known distributions of biological resources is a requirement that powerfully enhances impact assessments. Also, a "hands-on" tool that would enable the dredging project manager or resource agency representatives to specify a range of simulated scenarios and have model solutions quickly and readily available for interpretation would be a significant improvement over existing technologies.

Given these considerations, SSFATE is being developed to fulfill an obvious need for a modeling tool that can be easily customized to simulate a broad spectrum of dredging scenarios, accommodating essentially any hydrodynamic setting and most typical dredge plants. SSFATE is not intended to be an analytical tool per se, but rather a screening tool. Its utility is particularly suited for assessing the likelihood that resuspended sediments generated by a specific project would pose substantial risk to resources or habitats of concern, thereby allowing environmental windows to be appropriately applied or modified. Obviously, if SSFATE output showed negligible overlap of suspended/deposited sediments and resource distributions, the need for a stringent window to avoid conflicts would be questionable. Conversely, where output from SSFATE indicated a high probability of impact, an individual window could be accepted with a higher degree of confidence in its technical justification, and lead to consideration of other means to minimize impacts.

SYSTEM OVERVIEW: SSFATE is a versatile computer modeling system containing many features. For example, ambient currents, which are required for operation of the basic computational model, can either be imported from a numerical hydrodynamic model or drawn graphically using interpolation of limited field data. Model output consists of concentration contours in both horizontal and vertical planes, time-series plots of suspended sediment concentrations, and the spatial distribution of sediment deposited on the sea floor. In addition, particle movement can be animated over Geographic Information System (GIS) layers depicting sensitive environmental areas.

SSFATE employs a shell-based approach consisting of a color graphics based, menu-driven user interface, GIS, environmental data management tools, gridding software, and interfaces to supply input and display output data from the model. SSFATE runs on a personal computer and makes extensive use of the mouse (point/click) and pulldown menus. Data input/output is interactive and mainly graphics based. The system supports a full set of tools to allow the user to import data from standard databases, a wide variety of GISs, and other specialized plotting/analysis programs. SSFATE can be set up to operate at any dredging operation site and includes a series of mapping/analysis tools to facilitate applications. Initial setup for new locations of dredging operations can normally be accomplished in a few hours, unless numerical hydrodynamic models are run to provide flow fields. At the heart of the system is a computational model that predicts the transport, dispersion, and settling of suspended dredged material released to the water column as a result of dredging operations. An integral component of the modeling system is the specification of the sediment source strength and vertical distribution.

SSFATE SEDIMENT SOURCES: At the present time, sediment sources in SSFATE represent the introduction of sediment into the water column only as the result of a cutterhead dredge, a hopper dredge, or a clamshell dredge. The strength of each source is based on the Turbidity Generation Unit concept proposed by Nakai (1978). For the cutterhead dredge source, introduction of

suspended material is assumed to occur very near the bottom. For dredging operations using a hopper dredge, both near-bottom and near-surface sources are modeled. Near-surface sources are needed if overflow operations are performed. Clamshell dredges release material continuously as the clamshell is pulled through the water column. Thus, the vertical distribution of suspended sediment released by a clamshell dredge extends over the entire water column. In addition, since overflow operations can occur with the placement of material into a barge using a clamshell dredge, a near-surface source is also implemented for clamshell dredges. A detailed discussion of the sediment sources in SSFATE is provided in Johnson and Parchure (1999).

Simulation durations with SSFATE are not anticipated to be greater than a day or so. Thus, although the sources for cutterhead and clamshell dredges can move during the day, the greatest movement of the sediment source will occur with a hopper dredge. To account for this movement, the user specifies a line along which dredging takes place at a specified rate. When the hoppers are full, the simulated dredge moves to the placement site and releases the material. When the dredge returns to the dredging site, a new dredging line is specified. This procedure continues until the simulation is completed.

COMPUTATIONAL MODEL: Depending on the resolution of the numerical grid employed, SSFATE can make predictions very near dredging operations; however, the processes modeled are primarily far field processes in which the mean transport and turbulence associated with ambient currents dominate. Transport and dispersion of suspended material from a sediment source are predicted by a particle-based model using a random walk procedure.

The following basic equations determine the location of each particle at the next time-step in the simulation:

$$X^{n+1} = X^n + DX \tag{1}$$

$$Y^{n+1} = Y^n + \Delta Y \tag{2}$$

$$Z^{n+1} = Z^n + \Delta Z \tag{3}$$

where

$$\Delta X = U\Delta T + L_x \tag{4}$$

$$\Delta Y = V\Delta T + L_y \tag{5}$$

$$\Delta Z = Ws_i\Delta T + L_z \tag{6}$$

and

X,Y,Z = location of particle in the x-, y-, and vertical directions, respectively

U,V = mean ambient velocity in the x-, and y-directions, respectively

ΔT = time-step

Ws_i = settling velocity of particle class i

L_x, L_y, L_z = particle diffusion distance in the x-, y-, z-directions, respectively

Particle diffusion is assumed to follow a simple random walk process. A diffusion distance defined as the square root of the product of an input diffusion coefficient and the time-step is decomposed into X and Y displacements via a random direction function. The Z diffusion distance is scaled by a random positive or negative direction. The equations for the horizontal and vertical diffusion displacements are written as:

$$L_x = \sqrt{D_h \Delta T} \cos(2\pi R) \tag{7}$$

$$L_y = \sqrt{D_h \Delta T} \sin(2\pi R) \tag{8}$$

$$L_z = \sqrt{D_z \Delta T} \, (0.5 - R) \tag{9}$$

where

D_h, D_z = horizontal and vertical diffusion coefficients, respectively

R = random real number between 0 and 1

The particle model allows the user to predict the transport and fate of classes of settling particles, e.g., sands, silts, and clays. The fate of multicomponent mixtures of suspended sediments is predicted by linear superposition. The particle-based approach is extremely robust and independent of the grid system. Thus, the method is not subject to artificial diffusion near sharp concentration gradients and is easily interfaced with all types of sediment sources. For example, although the basic purpose of SSFATE is to aid in answering questions concerning the need for environmental windows associated with a dredging operation, models such as STFATE (Short-Term FATE) (Johnson and Fong 1995), which computes the near field dynamics of a placement operation, could be used to provide the sediment source associated with placement operations. In addition, under the Dredging Operations and Environmental Research (DOER) Program, a near field model is being developed to answer mixing zone questions connected with the placement of dredged material by a pipeline. Plans call for implementing results from the pipeline model as a sediment source in SSFATE.

Equations 4-6 show that the components of the ambient current field are required to transport the sediment particles. SSFATE provides two options for the user. The simplest option is to input limited field data, e.g., the magnitude of the tidal current, its period, and its principal direction. An interpolation scheme described by Cressman (1959) is then employed to "paint" a flow field over a rectangular water-land numerical grid. This flow field is then used to provide the (U, V) components of the ambient current in Equations 4 and 5. With this option, there is no vertical component of the flow field. The second option is for the user to import a time-varying,

three-dimensional (3-D) flow field generated by a numerical hydrodynamic model such as CH3D (Curvilinear Hydrodynamics in 3 Dimensions) developed by Johnson et al. (1991).

As implied by these two options, two types of grids are allowed in SSFATE. If currents are painted, the grid is rectangular with rectangular cells that are either land or water cells. Figure 1 shows an example of such a grid generated for upper Narragansett Bay, Rhode Island.
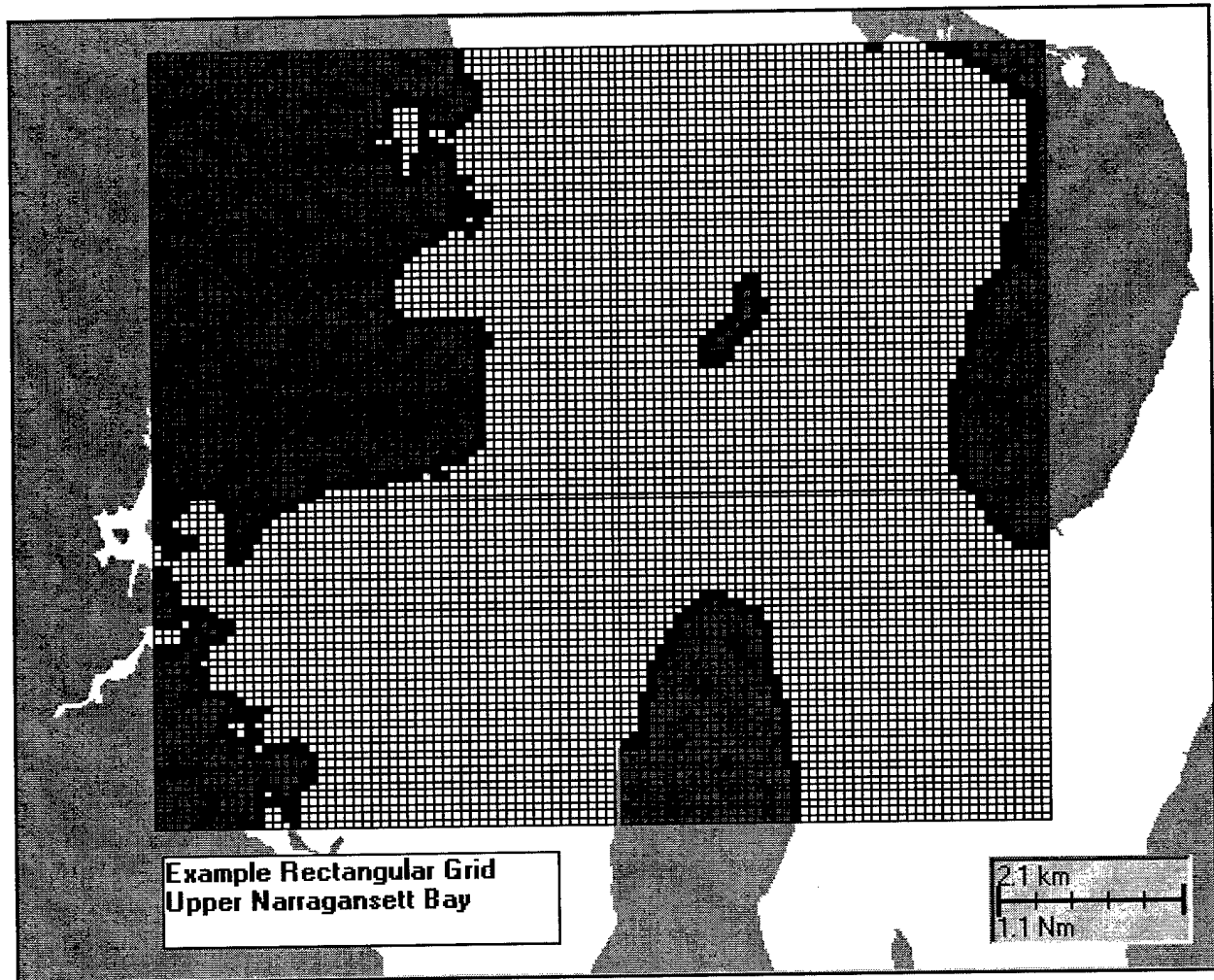

Figure 1. Rectangular land-water grid supported by SSFATE, upper Narragansett Bay, Rhode Island

However, if 3-D hydrodynamics are imported, SSFATE supports either a rectangular or a boundary-fitted curvilinear grid such as shown in Figure 2, again for the upper Narragansett Bay.

In addition to transport and dispersion, sediment particles also settle at some rate from the water column. Settling of mixtures of particles, some of which may be cohesive in nature, is a complicated process with the different size classes interacting; i.e., the settling of one particle type is not independent of the other types. The procedure that has been implemented in SSFATE is described in the following paragraphs, taken from Teeter (in review).
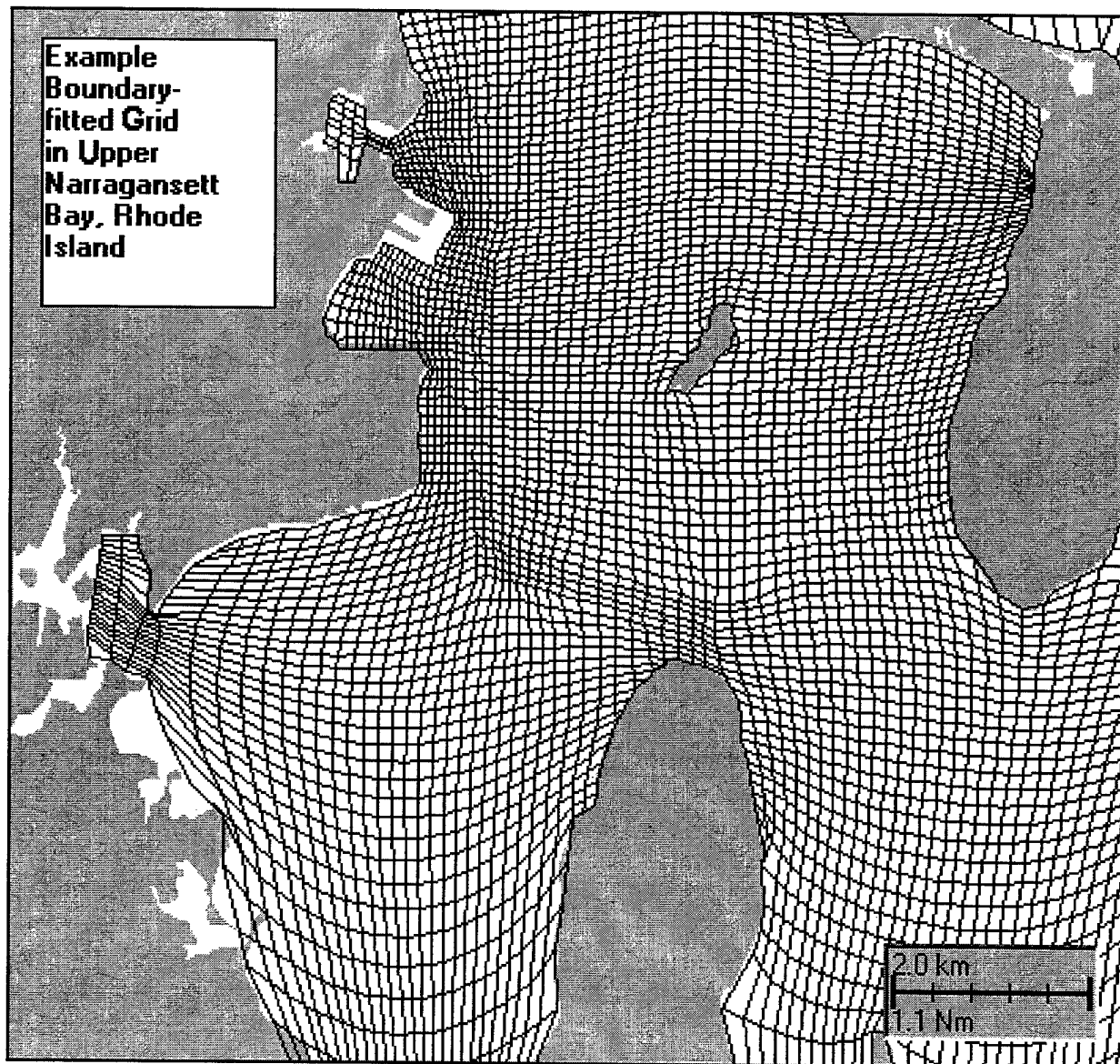
Figure 2. Boundary-fitted grid supported by SSFATE, upper Narragansett Bay, Rhode Island

At the end of each time-step the concentration of each sediment class C_i as well as the total concentration C is computed on a concentration numerical grid. The size of all grid cells is the same relative to one another and to time, with the total number of cells increasing as the suspended sediment plume moves away from the dredging source. The settling velocity of each particle size class is computed from

$$Ws_i = a \left(\frac{C}{\overline{C_{u\ell}}} \right)^{n_i}$$

$$(10)$$

$$a = \frac{1}{C}\sum_i a_i C_i \tag{11}$$

$$\overline{C}_{u\ell} = \frac{1}{C}\sum_i C_{u\ell_i} C_i \tag{12}$$

$$\overline{C}_{\ell\ell} = \frac{1}{C}\sum_i C_{\ell\ell_i} C_i \tag{13}$$

and $C_{u\ell_i}$ and $C_{\ell\ell_i}$ are the nominal upper and lower concentration limits, respectively, for enhanced settling of grain class i.

If $C \geq \overline{C}_{u\ell}$ then

$$Ws_i = a \tag{14}$$

whereas, if $C \leq \overline{C}_{\ell\ell}$ then

$$Ws_i = a\left(\frac{\overline{C}_{\ell\ell}}{\overline{C}_{u\ell}}\right)^{n_i} \tag{15}$$

Typical values of $C_{\ell\ell_i}$, $C_{u\ell_i}$, a_i, and n_i for four size classes are given in Table 1.

The next step in the settling computations is to compute a bottom shear

Table 1
Typical values of coefficients

Class	Size, microns	$C_{\ell\ell_i}$, g/cc	$C_{u\ell_i}$, g/cc	a_i, m/s	n_i
0	0-7 (clay)	50	1000	0.0001	1.33
1	8-35 (fine silt)	150	3000	0.0002	1.10
2	36-74 (coarse silt)	250	5000	0.0005	0.90
3	75-130 (fine sand)	400	8000	0.010	0.80

stress τ using either the painted currents or the imported currents. A deposition probability P_i is then computed for each size class as follows:

a. For size class 0 (clay), the following are used:

$$P_0 = \left(1 - \frac{\tau}{\tau_{cd}}\right), \text{ if } \tau < \tau_{cd} \tag{16}$$

$$P_0 = 0, \text{ if } \tau > \tau_{cd} \tag{17}$$

where τ_{cd} is the critical shear stress for deposition for the clay fraction.

b. For the other size classes, SSFATE uses

$$P_i = 0, \text{if } \tau \geq \tau_{u\ell_i} \tag{18}$$

$$P_i = 1.0, \text{if } \tau \leq \tau_{\ell\ell_i} \tag{19}$$

where

$\tau_{u\ell_i}$ = the shear stress above which no deposition occurs for grain class *i*

$\tau_{\ell\ell_i}$ = the shear stress below which the deposition probability for grain class *i* is 1.0

For values of τ between $\tau_{\ell\ell_i}$ and $\tau_{u\ell_i}$, linear interpolation is used.

Typical values for $\tau_{\ell\ell}$, and $\tau_{u\ell}$ are given in Table 2.

A typical value for τ_{cd} is 0.016 Pa.

Next, the deposition of sediment from each size class from each bottom cell during the current time-step is computed. The computations start with the largest size class:

**Table 2
Typical values for shear stresses, Pa**

Class	$\tau_{\ell\ell_i}$	$\tau_{u\ell_i}$
0	0.016	0.03
1	0.03	0.06
2	0.06	0.20
3	0.20	0.90

$$Flux_i = b_i \, C_i \, Ws_i \, P_i \tag{20}$$

where b_i is a probability parameter that includes all other factors influencing deposition other than shear.

This mass is then removed from the particles occupying the cell. The deposition for the remaining size classes is then computed, starting with the second largest size class and working down to the smallest. This deposition is computed as follows:

If $0 \leq P_i \leq 0.05$, then

$$Flux_i = \frac{C_i \, Flux_{i+1}}{C_{i+1} + 1} \tag{21}$$

otherwise,

$$Flux_i = b_i \, C_i \, Ws_i \, P_i \tag{22}$$

The following are typical values for the coefficient b_i for the four size classes previously presented:

- $b_0 = 0.2$
- $b_1 = 0.4$
- $b_2 = 0.6$
- $b_3 = 1.0$

APPLICATION ASPECTS: The first step in an application of SSFATE is to establish an operational area. Locations can range from rivers, lakes, and estuarine systems on a spatial scale of up to tens of kilometers. For each location, the user supplies digital data describing the shoreline and the bathymetry. These data can be digitized from an appropriate map, obtained from digital databases, or produced using an external GIS and imported into the system. The user may have as many locations in the system as computer storage allows and can rapidly change from one location to another by simply loading the appropriate data set into the application.

The embedded GIS allows the user to input, store, manipulate, analyze, and display geographically referenced information. The GIS has been designed to be user friendly, interactive, and fast. However, it does not have the ability for sophisticated mapping or logical set-based calculations. GIS data may not be required by a particular application, but are often helpful in analyzing and interpreting model predictions.

Additional information about geographically referenced data can be obtained through the use of linking procedures. These link files may include charts, graphics, tables, tutorials, bibliographies, text, photographs, or animations. Examples of data that might be stored in the GIS include physical characteristics of the dredged material, details of the placement site location, current meter data sets, and distribution of potentially impacted biota.

A suite of tools is provided within the SSFATE modeling system to import, export, and manipulate environmental data. As an example, time series of scalar or vector data at single or multiple points can be imported. Spatial data can be imported for rectangular or boundary-fitted gridded regions. Through this procedure, data from external models (e.g., hydrodynamic models) or measuring systems (e.g., moored current meters) can be accessed and used as input to the SSFATE modeling system. Tools are also available to import/export data from/to other GISs and existing databases and to create/delete/edit databases in the embedded GIS.

Input data required include the shoreline (or a boundary-fitted numerical grid), bathymetry, ambient currents (either limited field data to generate painted currents or flow fields imported from a numerical hydrodynamic model), dredged material sediment characteristics, model parameters, and output display parameters. In general, spatial information input to SSFATE is handled through the gridding module of the GIS. Time-series data are addressed with environmental data management tools and model parameter options. Input to specify the sediment characteristics, source strengths and locations, and display options is managed through a set of model-specific input forms. Data input is largely based on graphical techniques since they are accurate and fast.

As noted, either a boundary-fitted grid can be imported or a rectangular land-water grid can be generated by SSFATE. For the case of a rectangular grid, the user can apply the suspended sediment fate model in any subdomain of the location area selected. The user identifies the subdomain of interest through its corner points and selects the appropriate grid size. A gridding algorithm is then used to generate a land-water rectangular grid system.

When the rectangular grid is generated, the user may edit the computer-produced grid to better conform to the shoreline or represent openings to restricted passages (e.g., between islands, narrow inlets, etc.). Editing is also useful to add features that are not given on the base map. Once completed, a bathymetric file is automatically generated and stored under a user-selected grid file name. Multiple grid files can be made to define different areas or the same area with various modifications.

SSFATE requires a flow field for execution of the particle tracking computations. As previously discussed, such a flow field can be generated or painted using limited field data (not a mass conservative field) or can be imported as output from a 3-D numerical hydrodynamic model on a boundary-fitted grid.

Model output includes animation of the particles representing each sediment type individually or all of the particles together. A typical snapshot from an animation of suspended sediment particles being transported away from a dredging site is presented in Figure 3. The output display system is designed so that the user can interact with the display window at any time during the trajectory view operation to obtain information on mass balance for a selected size class of particles. Additional model output includes both horizontal and vertical concentration contours of each sediment type or a superposition of all suspended sediment, time-series of suspended sediment concentrations at a particular point, spatial distribution of sediment deposited on the sea bottom, and tabular summaries of how much sediment is in suspension, how much has been deposited, and how much has left the grid. A contouring procedure is available to provide dredged material thickness distributions on the sea bottom and concentrations at user-defined depths in the water column. The user may select the contour intervals and threshold value. The user can interact with the contoured data to obtain pertinent information such as a cross-sectional view along a user-selected transect, the distance to features from the sediment source, and the area covered by material that has been deposited on the bottom.

CONCLUSIONS: A personal computer based modeling system called SSFATE for computing suspended sediment concentrations resulting from dredging operations has been presented and its major components have been described. SSFATE can be used anywhere in the world and provides an integrated and unified system to support data display, model application, and interpretation of results.

SSFATE has been developed to satisfy a specific need for tools to aid in negotiation of environmental windows. Predetermined attributes of such a tool included adaptability to a broad spectrum of dredging project scenarios, low "front end" requirements for input data or supporting hardware, efficient computational algorithms to enable multiple simulations in a short period of time, and effective means of output visualization. The strengths of SSFATE are in its versatility, simplicity, efficiency, and low cost of operation. In tandem with other tools being developed under the auspices of the DOER Program Environmental Windows Focus Area (e.g., FISHFATE, see Ault, Lindeman,
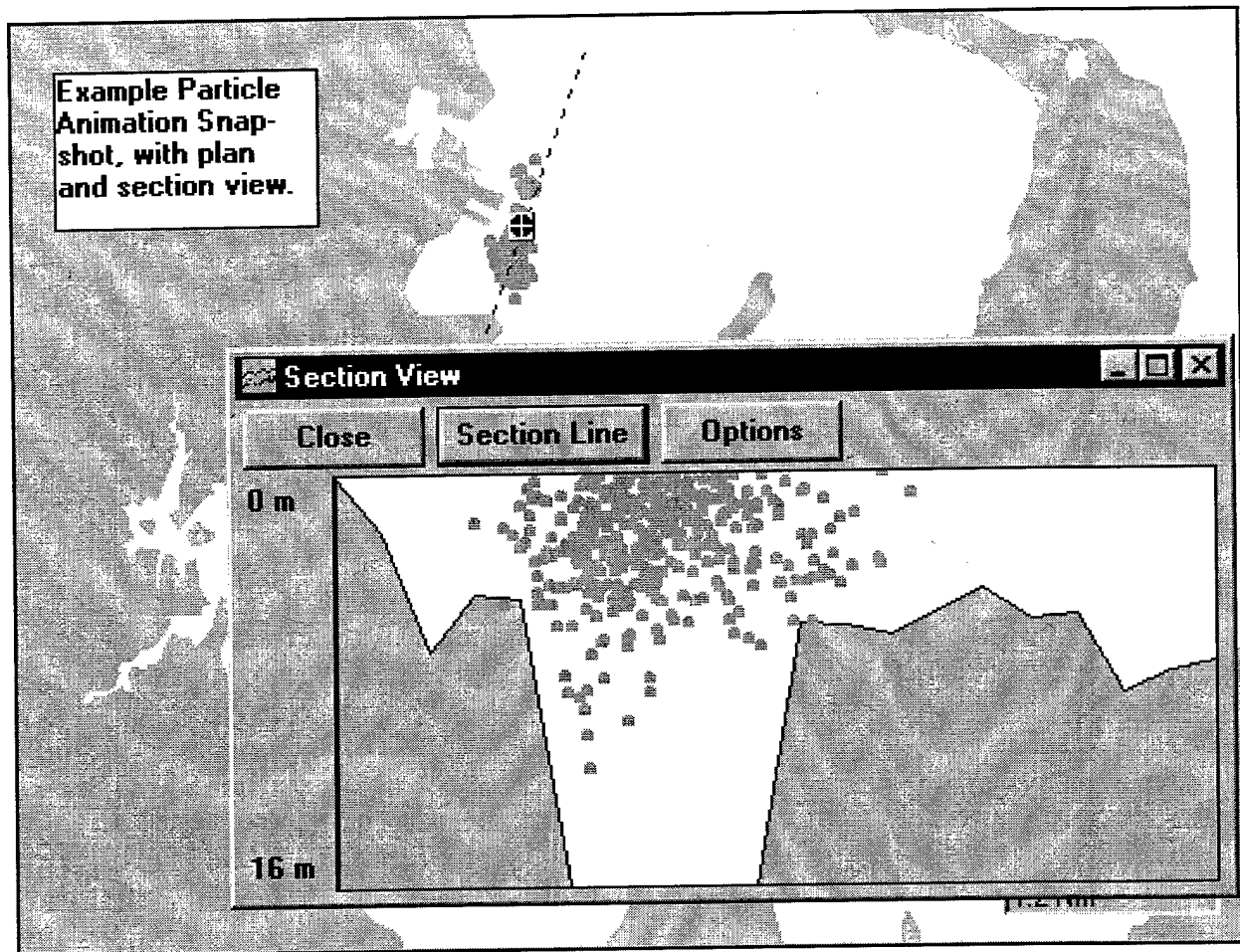
Figure 3. Snapshot from an animation of sediment particles

and Clarke 1998), SSFATE represents a significantly improved capability for dredging project assessments. Dredging project managers and resource agency staff should be able to rapidly explore the effects of model parameters on expectations of impacts, and to optimize their management options, including environmental windows, based on SSFATE results.

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